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1 **Title:** Food and bioenergy: exploring ideotype traits of a dual-purpose wheat cultivar

2 **Running title:** Assessing wheat cultivars for use for fuel and food

3

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9

10 **Abstract**

11 Lignocellulosic biofuels, such as those produced from crop residues, offer the
12 possibility of reducing GHG emissions in the transport sector. Wheat straw is one
13 potential feedstock for these fuels but grain yield has been prioritised over straw
14 yield in crop breeding as straw currently has limited value. Should a new market for
15 straw develop then dual-purpose cultivars (DPCs) that are optimised for food and
16 bioenergy may become desirable. Field experiments were used to assess four key
17 traits – grain yield, straw yield, lodging resistance and straw saccharification
18 potential (i.e. the biofuel yield) – of a selection of modern and older UK wheat
19 cultivars (with release dates ranging from 1964 to 2010) with the aim of identifying
20 dual-purpose cultivars and any trade-offs among the key traits. None of the cultivars
21 assessed were outstanding candidates for use as DPCs. Among the semi-dwarf

22 cultivars there were only minor relationships between traits; including the non-semi-
23 dwarf cultivar showed trade-offs between grain and straw yields. The findings
24 suggest that selecting from among currently grown cultivars offers limited possibility
25 for growing truly DPCs. However, the results indicate that high straw yields can be
26 achieved by selecting high grain-yielding cultivars and managing these to maximise
27 grain yield will also result in high straw yields. Plant growth regulators should
28 continue to be used as these do not significantly reduce straw yields but do decrease
29 lodging susceptibility.

30

31 **Keywords:** Lignocellulosic Biofuel; Wheat (*Triticum aestivum*); Dual-Purpose
32 Cultivars; Agronomy; Crop Physiology

33

34 **Abbreviations:** %GR (% glucose release); dual-purpose cultivars (DPC); field
35 experiments 1-3 (FE1-3); fusarium head blight (FHB); growth stage (GS); harvest
36 index (HI); nitrogen (N); nitrogen treatments 1-3 (N1-3); plant growth regulators
37 (PGRs); root failure wind speed (RFWS); stem failure wind speed (SFWS); straw
38 sections 1-4 (S1-4).

39 **1. Introduction**

40 Second-generation biofuels, such as fuels produced from lignocellulosic material,
41 offer the possibility of reducing greenhouse gas emissions and ensuring energy
42 security (Demirbas, 2008). European Union legislation is mandating the use of
43 biofuels in the transport sector; by 2020, 10% of transport fuel must be from
44 renewable sources, the majority of which is expected to be by biofuels (EU, 2009).
45 Currently the majority of biofuels are first generation liquid biofuels, produced from
46 starchy grains (such as wheat and maize); the use of these has been controversial due
47 to the potential land use competition between food and fuel production and
48 expansion of agricultural land (Sims et al., 2010). This has led to interest in biofuels
49 produced from lignocellulosic materials (e.g. crop and forestry residues, industrial
50 waste, and dedicated energy crops such as *Miscanthus*); as these are considered to be
51 waste products or able to be grown on marginal land, competition with food
52 production is limited. The technology has developed to the point that commercial
53 production of bioethanol from lignocellulosic material started in 2013 at Beta
54 Renewables' *Crescentino* plant in Italy and in 2014 at GranBio's *Bioflex 1* plant in
55 Brazil and the POET facility in Emmetsburg, US.

56 Wheat straw is the biggest resource available for SGB production in the UK
57 (Copeland & Turley, 2008); however, there are limitations in supply due to
58 competition with other straw uses (Glithero et al., 2013b), some farmers'
59 unwillingness to supply straw (Glithero et al., 2013a) and, as transporting
60 lignocellulosic material is expensive (Miao et al., 2012), supply is limited to the
61 local area. Dedicated energy crops could potentially be used but these would have to
62 be grown on marginal land to limit competition with food production. As there is

63 only limited marginal land available and farmers are often unwilling to grow these
64 crops (Glithero et al., 2015), their contribution is likely to be minor. This could mean
65 difficulties in matching a high enough density of supply for a biorefinery. Feasibility
66 of sufficient feedstock supply might, therefore, depend on increasing residue yields.
67 If this is possible without compromising grain yields then farmers might be
68 interested in growing cultivars with higher straw yields to increase the value of their
69 crops.

70 Dual-purpose cultivars (DPCs) offer the possibility of increasing the resources
71 available for lignocellulosic biofuel production without compromising existing food
72 production. The concept of a wheat DPC food and bioenergy ideotype is reviewed in
73 Townsend et al. (2015); in that review four key traits are highlighted: grain yield,
74 straw yield, straw saccharification potential (i.e. the amount of sugars made
75 accessible during enzymatic hydrolysis for conversion to biofuel) and lodging
76 resistance.

77 Improving all traits simultaneously might not be possible due to trade-offs among the
78 traits. The reason that lodging resistance is included in the traits of a DPC is because
79 of potential trade-offs with saccharification potential and straw yields. High straw
80 yields could also lead to greater risk of lodging due to the relationship between plant
81 height and straw yield (Larsen et al., 2012) and the correlation between plant height
82 and lodging risk (Berry et al., 2000). For straw saccharification potential it has been
83 hypothesised that breeding for increased lodging resistance has lowered straw
84 saccharification potential through changing the stem material characteristics (Travis
85 et al., 1996). It is also possible that this could increase the risk of disease
86 susceptibility making the plant more susceptible to pathogens and pests (Li et al.,

2008). Alongside these trade-offs is the possibility that high straw yields could come at the expense of grain yield due to competition for a limited quantity of assimilates (Austin et al., 1980).

As discussed in Townsend et al. (2015), other management practices might also influence these key traits and, therefore, could be used to maximise these traits. In particular, plant growth regulator (PGR) application, nitrogen (N) fertiliser rate and combine harvester cutter height could have impacts on straw yields and other characteristics. These management practices could potentially lead to trade-offs by improving some traits at the expense of others.

Variation among cultivars exists for all four traits identified but as straw yield and, in particular, saccharification potential, are only very rarely quantified there is limited data on these traits in modern cultivars. Larsen et al. (2012), exploring a similar concept, assessed the biofuel potential of multiple wheat cultivars, measuring grain and straw yields, and straw saccharification potential.

The aim of this paper is to quantify straw and grain yields, lodging susceptibility and straw saccharification potential in a number of UK winter wheat cultivars (introduced between 1968 and 2010) with the purpose of identifying potential candidates for use as dual-purpose food and bioenergy cultivars. Field experiments over three years were conducted to measure the traits in these cultivars and to determine whether trade-offs exist among these desirable traits.

107 **2. Materials and Methods**

108 **2.1 Field experiments**

109 Three field experiments were conducted at the University of Nottingham's farm at
110 Sutton Bonington (52°50'N, 1°15'W) between 2009 and 2012. Key details of these
111 experiments are given in **Table 1**. Multiple winter wheat cultivars were assessed for
112 their traits for use as DPCs (see **Table 2** for a list of the cultivars assessed); these
113 cultivars were selected to provide a wide range of material in terms of date of
114 introduction, height, lodging resistance and grain end-use. These included a non-
115 semi-dwarf cultivar (Maris Widgeon) while the rest were semi-dwarf cultivars. The
116 soil type was a stony sandy loam soil (Dunington Heath series). Cultivars were
117 grown in plots of size 24 x 1.6 m. Crop protection chemicals were used
118 prophylactically to minimise weeds, pests and diseases in all years. Soil fertility
119 levels were amended to ensure nutrient availability would not be limiting. Rainfall
120 and average temperature for the growing seasons are shown in **Fig. 1a, b**.

121 Field experiment 1 (FE1) took place in the 2009-2010 growing season. It consisted
122 of four completely randomised blocks of 40 winter wheat cultivars, with a subsection
123 of 14 cultivars used in the analysis. PGRs were not applied in order to allow full trait
124 expression. Each block was separated by a discard plot.

125 Field experiment 2 (FE2) took place in the 2010-2011 growing season. An additional
126 cultivar, Glasgow, was added to the 14 cultivars assessed in FE1. The cultivars were
127 grown in a split-plot design with the plant growth regulator Chlormequat (PGR+) and
128 without (PGR-) as the main plots. The experiment was organised in three blocks

129 with the cultivars randomly distributed within the main plots and the blocks
130 separated by discard plots.

131 Field experiment 3 (FE3) took place in the 2011-2012 growing season. Only three
132 cultivars were considered to allow a focus on management practices. The PGR
133 treatments matched those of the previous field experiment. The N treatments were
134 based on the N requirements of the field (based on RB209, 2010); all plots were
135 given the first two splits of 40 kg ha⁻¹ and 80 kg ha⁻¹ with a final split of 0 kg ha⁻¹
136 (N1), 50 kg ha⁻¹ (N2) or 100 kg ha⁻¹ (N3; fertiliser application timing is given in
137 **Table 1**). The N2 treatment matched the recommended N application rate for the
138 particular field, rotation and crop conditions. The three cultivars assessed – Cordiale,
139 Grafton and Xi19 – were from the previous year’s experiment and were selected
140 based on current use (all three were in AHDB’s 2011 Recommended List for wheat
141 cultivars), high grain yields and differing characteristics in terms of height and
142 lodging susceptibility. A split-split plot design was used whereby each block was
143 divided into three main plots (N treatment) that were each subdivided into two sub-
144 plots (PGR treatment). Cultivars were then randomised within the sub-plots.

145 **2.2 Biomass assessments**

146 Stem number was counted prior to harvest in FE1 and FE2 while in FE3 plant
147 number and average tiller number were counted at GS61 (based on the decimal
148 system described in Zadoks et al., 1974). When the crops were fully mature, a 0.5 x
149 0.5 m area was randomly sampled from each plot and cut at soil level. Plant height
150 was measured to the tip of the ear. The above ground dry matter (AGDM) of the
151 sample was determined by drying to constant mass, and then the ears were separated

152 from the stems and threshed so that straw, grain and chaff weight could be
153 determined. In FE3, the stem was split into sections to investigate the effect of
154 combine harvester cutter height on straw yield; firstly, the leaf blades were removed
155 then the stem was split into the first 10 cm from ground level (S1), 10-15 cm from
156 ground level (S2), 15-20 cm from ground level (S3) and the remainder (S4). These
157 simulated combine cutter heights of 10 cm, 15 cm and 20 cm and allowed
158 determination of the amount of harvestable straw (i.e. the straw amount excluding
159 the stubble and friable material that would be left on the field during straw
160 harvesting).

161 **2.3 Saccharification potential assessments**

162 Sugar composition of the straw was assessed for a subset of cultivars from FE1 and
163 FE2. These assessments followed the methodology given in Ibbett et al. (2011).
164 Whole plant samples from ground level to the top of the peduncle were milled to
165 obtain homogenous samples with particle sizes of 200-700 microns. The milled
166 straw (30 mg) was subjected to a Saeman acid hydrolysis and the glucose and xylose
167 content of the resultant hydrolysate were measured using high-performance anion
168 exchange chromatography with pulsed amperometric detection (HPAEC-PAD).

169 Milled samples (1 g) were then subjected to a standardised dilute acid pre-treatment
170 (10% w/v, 1% H₂SO₄, 121°C, 15 m), the residue was washed in distilled water then
171 dried and subjected to a Saeman hydrolysis before HPAEC-PAD was used to
172 quantify the glucose present. Dried residue (200 mg) was then incubated with
173 cellulase cocktail (Cellitec2) and saccharification potential assessed as the amount of

174 monomeric sugars released during hydrolysis for 72 h, which were quantified using
175 HPAEC-PAD.

176 Saccharification potential is given as the glucose yield released during enzymatic
177 hydrolysis per unit of pre-treated straw (expressed as mg of glucose released per g
178 pre-treated straw). Percentage glucose release (%GR) is expressed as the percentage
179 of total available glucose in the pre-treated residue released during enzyme
180 hydrolysis.

181 **2.4 Lodging assessments**

182 To determine lodging resistance for the different treatments, the lodging model
183 outlined in Baker et al. (1998) and Berry et al. (2003) was used to determine the
184 failure wind speed (i.e. the minimum wind speed at which lodging will occur). The
185 model uses measurements of plant characteristics to allow calculation of the material
186 strength of the lower internodes, the strength of the root-soil interface and the stem
187 leverage force (Berry et al., 2000). When the stem leverage force exceeds the
188 material strength of the lower internodes, the stem bends or breaks leading to stem
189 lodging; the wind speed at which stem lodging occurs is called stem failure wind
190 speed (SFWS). When the plant leverage force exceeds the anchorage strength the
191 roots are displaced within the soil. The wind speed at which root lodging occurs is
192 called root failure wind speed (RFWS).

193 Ten plants were carefully removed from each plot on 1 July 2010 (FE1), 28 June
194 2011 (FE2) and 17 July 2012 (FE3) when the plants were at approximately GS75.
195 The plants were placed in polythene bags and stored at 4°C for no more than 2 weeks
196 until laboratory analysis. In the laboratory, eight of these plants were taken for

197 measurement of lodging traits, as detailed in Berry et al. (2000). Structural rooting
198 depth and average root plate spread were measured to calculate the strength of the
199 root-soil interface. Stem leverage force was calculated by isolating the main stem and
200 measuring natural frequency, number of ears per plant, ear area and height at centre
201 of gravity. Stem material strength for internodes one and two were determined by
202 measuring internode length, diameter, wall width and breaking strength. The
203 equations for calculating stem material strength and stem leverage force, as well as
204 SFWS and RFWS are given in Berry et al. (2003). For each of the eight plants the
205 SFWS and RFWS and these eight failure wind speeds were averaged to give a SFWS
206 and RFWS for each plot.

207 **2.5 Statistical analysis**

208 Analysis of variance (ANOVA) with blocking procedures appropriate for the
209 experimental design was carried out using GenStat for Windows, 15th Edition (VSN
210 International Ltd.). Data was checked to see if it met the assumption of constant
211 variance and normal distribution of residuals. All yield data was converted into
212 tonnes per hectare and 15% moisture content to enable comparison to standard
213 cultivar trial data. ANCOVA was used to investigate the relationships between traits.
214 For comparison across years, all treatments not common to the three field
215 experiments were excluded.

216 3. Results

217 The weather varied greatly between the years. In FE2 there was low rainfall
218 throughout the growing season, but especially in spring, and a colder than average
219 December. In FE3 rainfall was low at the start of 2012, but other than May, monthly
220 rainfall was far higher than average; because of the high rainfall during June and
221 July, the plants developed considerable fungal disease. High levels of fusarium head
222 blight (FHB) were observed as well as other fungal diseases.

223 3.1 Biomass production and partitioning

224 The cultivar Battalion had a greater number of stems compared to the other cultivars
225 ($P = 0.002$). In FE2, stem number did not significantly differ with cultivar or PGR. In
226 FE3, stem number was assessed at GS61 and Xi19 had significantly fewer stems than
227 Grafton or Cordiale ($P < 0.001$) but neither PGR nor N affected stem number.

228 In FE1 and FE2 there were no significant differences in AGDM (**Tables 3 and 4**,
229 respectively). Although there was a large range of mean AGDMs, the high variation
230 among replicates meant significant differences were not detected. In FE2, PGR
231 application did not significantly affect AGDM. In FE3, Xi19 had significantly lower
232 AGDM than Grafton and Cordiale ($P = 0.017$) but neither PGR nor N had an
233 influence (**Table 5**). AGDM was significantly higher in 2012 than 2010, with 2011
234 having an intermediate AGDM ($P = 0.035$).

235 In FE1, there were significant differences in grain yield between the highest yielding
236 cultivar, Cordiale, and the lowest yielding cultivar, Maris Widgeon ($P = 0.048$) but
237 not among the other cultivars (**Table 3**). In FE2, there was a significant difference in

238 grain yield ($P < 0.001$) with Maris Widgeon having a significantly lower grain yield
239 than the majority of the other cultivars (**Table 4**). PGR application had no effect on
240 grain yields. In FE3, grain yield for Xi19 was significantly lower than that of Grafton
241 and Cordiale ($P < 0.001$; **Table 5**); grain yield was not affected by N application level
242 but was significantly higher with PGR application ($P = 0.040$). When comparing
243 years, there was a significant interaction between cultivar and year ($P = 0.036$); grain
244 yields were highest in FE2 for all cultivars but Grafton had a much lower grain yield
245 than the other cultivars in FE1 while Xi19 had a much lower grain yield in FE3.

246 For straw yield, there were significant differences between cultivars in FE1 ($P =$
247 0.005) and FE2 ($P < 0.001$; **Tables 3 and 4**). However, in FE1, the difference was
248 only significant between the highest yielding cultivar, Maris Widgeon, and the four
249 lowest yielding cultivars, Grafton, Quartz, Zebedee and Sterling, while in FE2, Maris
250 Widgeon had significantly more straw than all the other cultivars. There was a
251 general trend for higher straw yields when PGRs were not used but this was not
252 significant. In FE3 straw yield was not significantly influenced by cultivar, PGR or
253 N. Excluding the leaf blades (leaving just stem and leaf sheath) did not lead to
254 significant differences between the treatments. Straw yields were significantly higher
255 in FE3 than the first two field experiments ($P < 0.001$) but across the three years there
256 was no significant difference in straw yield between the cultivars.

257 Splitting the stem into sections allows an assessment of the influence that combine
258 harvester cutter height might have on straw yields. At a cutter height of 10 cm there
259 was a significant cultivar effect ($P = 0.036$) with Xi19 having significantly higher
260 straw yield than Grafton, with Cordiale having an intermediate yield, matching
261 height order (**Table 6**). At a cutter height of 15 cm PGR application significantly

lowered straw yield ($P = 0.036$), while percentage difference in yield between Xi19 and Grafton increased from 4.1% to 5.5% ($P = 0.007$). At a cutter height of 20 cm the percentage difference in yield between Xi19 and Grafton increased to 7.0% ($P = 0.001$) and the percentage difference in yield between PGR treatments increased from 5.5% to 7.3% ($P = 0.009$). However, from a practical viewpoint, these significant differences are actually relatively minor. For example, the difference in straw yield between Grafton and Xi19 at a cutter height of 10 cm is 0.40 t ha^{-1} but this only increases to 0.49 t ha^{-1} at a cutter height of 20 cm.

Assuming that the lower 10 cm remain on the field as stubble and the leaf blades are lost during baling, on average 61% of the total leaf and stem material is harvested. The proportion of total straw that is 'harvestable straw' varied with cultivar ($P < 0.001$) ranging from 58% for Grafton to 63% for Xi19. Although PGR application lowered this ratio ($P = 0.013$) the actual difference was inconsequential with 61% collected when no PGRs were applied compared to 60% for treated plants. These results suggest that assuming 60% recovery of straw is a suitable approximation regardless of cultivar and PGR treatment; however, it is unclear whether this percentage recovery would be seen with the cultivars from FE1, which were considerably shorter.

In FE1, harvest index (HI) significantly varied with cultivar ($P < 0.001$) with Maris Widgeon having a much lower HI than other cultivars (**Table 3**). In FE2, HI significantly varied with cultivar ($P < 0.001$) ranging from 0.43 for Maris Widgeon to 0.61 for Grafton (**Table 4**). In FE3, HI significantly varied with cultivar ($P < 0.001$), being significantly lower in Xi19 than Cordiale and Grafton (**Table 5**). When comparing years, HI was similar in FE1 and FE2 but significantly lower in FE3 (P

286 <0.001). Xi19 also had a significantly lower HI than the other cultivars in all three
287 years ($P = 0.001$).

288 **3.2 Saccharification potential**

289 In FE1, glucose yields and xylose yields for untreated straw did not significantly
290 differ with cultivar (**Table 7**). After pretreatment, glucose yield did not significantly
291 differ with cultivar. Straw saccharification potential differed significantly between
292 cultivars ($P < 0.001$) with Maris Widgeon showing much lower saccharification
293 potential than the other cultivars in both years. This is reflected in %GR with Maris
294 Widgeon having a lower value than the other cultivars ($P < 0.001$).

295 As with FE1, in FE2 glucose yields and xylose yields for untreated straw did not
296 significantly differ with cultivar (**Table 8**) or with PGR. After pretreatment, glucose
297 yield did not significantly differ with cultivar or PGR. Straw saccharification
298 potential differed significantly between cultivars ($P < 0.001$) with Maris Widgeon
299 having a much lower saccharification potential, which is also reflected in %GR with
300 Maris Widgeon having a lower value than the other cultivars ($P < 0.001$). PGR did
301 not significantly influence saccharification potential or %GR.

302 **3.3 Lodging assessments**

303 In all three years, SFWS was lower than RFWS indicating that stem lodging was
304 more likely to occur. Average SFWS in FE3 was 10.62 m s^{-1} (**Table 10**), which was
305 much lower than the 18.65 m s^{-1} in FE1 (**Table 8**) but very similar to the 10.66 m s^{-1}
306 in FE2 (**Table 9**). FE1 had lower stem leverage force and greater stem material
307 strength than FE2 and FE3, leading to greater lodging resistance.

308 In FE1, SFWS differed significantly between cultivars ($P < 0.001$) with Zebedee
 309 having a significantly lower SFWS and Grafton and Quartz having significantly
 310 higher SFWS (**Table 8**). Maris Widgeon had the second lowest SFWS. In FE2
 311 SFWS differed significantly among cultivars ($P < 0.001$) with Grafton having
 312 significantly higher SFWS than the majority of the other cultivars (**Table 9**).
 313 Although Maris Widgeon was much taller than the other cultivars it was less
 314 susceptible to lodging than some of the semi-dwarf cultivars; its high leverage force
 315 was partly offset by a high material strength. As expected, PGR application
 316 significantly increased SFWS ($P = 0.026$), due to lower leverage force. In FE3, Xi19
 317 had significantly lower SFWS than Cordiale or Grafton ($P < 0.001$; **Table 10**). As
 318 with FE2, PGR application significantly lowered the risk of lodging ($P = 0.001$).

319 In FE1, leverage force on internodes 1 and 2 significantly differed with cultivar (P
 320 < 0.001), with Maris Widgeon having the greater leverage force. Height at centre of
 321 gravity (HCG) is a major determinant of leverage force and this significantly varied
 322 with cultivar ($P < 0.001$; **Table 8**).

323 In FE2, leverage force on internode 1 was influenced by cultivar and PGR
 324 application ($P < 0.001$) as was leverage force on internode 2 ($P < 0.001$ and $P =$
 325 0.001 , respectively; **Table 9**). In FE2 and FE3 there was a significant interaction
 326 between PGR and cultivar ($P = 0.002$ and $P = 0.005$, respectively); leverage force
 327 was lower after PGR application for all cultivars but the extent of this varied with
 328 cultivar. This reflected the significant interaction between PGR and cultivar in
 329 determining the HCG ($P = 0.002$) with some cultivars having much greater
 330 reductions in HCG with PGR application; interestingly, percentage reduction in plant
 331 height was not related to original plant height.

332 In FE3, leverage force for internodes one and two was much higher for Xi19 (P
333 <0.001 for both) reflecting the greater height of Xi19 and the lower natural
334 frequency. Leverage force was also greater for plants without PGRs ($P = 0.001$ and
335 <0.001 for internodes one and two respectively). Interestingly leverage force was
336 lower for N1 treatment compared to the other N treatments ($P = 0.041$ and 0.035 for
337 internodes one and two respectively); however, when considering individual
338 parameters that combine to give leverage force, N did not significantly affect these.
339 For material strength of internode 1 there was a significant interaction between
340 cultivar, nitrogen and PGR; this resulted from the material strength of internode 1 of
341 Cordiale without PGRs being much higher than for N1 and N3, while for other
342 cultivars with and without PGRs the material strength did not vary with nitrogen
343 treatment.

344 Differences between cultivars in stem material strength were not significant for
345 internodes 1 and 2 in FE1 (**Table 9**). Cultivar significantly affected stem material
346 strength for internode 1 in FE2 (**Table 10**; $P = 0.002$) but not internode 2.

347 In FE3 the material strength of internode 1 was significantly higher for Cordiale than
348 the other cultivars ($P <0.001$) but was not influenced by PGR or N. For internode 2,
349 Grafton was significantly lower than Xi19, which in turn was significantly lower
350 than Cordiale ($P <0.001$). Neither PGR nor N had an influence.

351 **3.4 Relationships between traits**

352 **3.4.1 Grain and straw yields**

353 For FE1 and FE2 (without PGRs) there was a strong positive relationship between
354 straw yield and grain yield ($P < 0.001$) with a significant difference between FE1 and
355 FE2 due to the difference in yield between the field experiments (adj. $R^2 = 0.44$.
356 Regression lines: $y = 0.3264x + 2.197$ [FE1]; $y = 0.3264x + 2.971$ [FE2]). This
357 relationship is skewed slightly by the inclusion of Maris Widgeon, which had high
358 straw yields but low grain yield.

359 **3.4.2 Straw saccharification potential and lodging resistance**

360 SFWS was positively related to saccharification potential ($P < 0.001$; adj. $R^2 = 0.86$.
361 Regression lines: $y = 0.01685x + 12.71$ [FE1]; $y = 0.01685x + 3.30$ [FE2]). This was
362 despite the negative relationship between saccharification potential and material
363 strength of internode 1 ($P = 0.004$; adj. $R^2 = 0.17$. Regression lines: $y = -0.728x +$
364 358.2 [FE1]; $y = -0.728x + 392.5$ [FE2]) and internode 2 ($P < 0.001$; adj. $R^2 = 0.27$.
365 Regression line: $y = -2.488x + 399.6$). However, as leverage force increases,
366 saccharification potential decreases for both internode 1 ($P < 0.001$; adj. $R^2 = 0.57$.
367 Regression lines: $y = -0.4406x + 272.2$ [FE1]; $y = -0.4406x + 340.53$ [FE2]) and
368 internode 2 ($P < 0.001$; adj. $R^2 = 0.62$. Regression lines: $y = -0.4119x + 245.2$ [FE1];
369 $y = -0.4119x + 315.3$ [FE2]) reflecting the reduction in saccharification potential
370 with increasing plant height ($P < 0.001$; adj. $R^2 = 0.74$. Regression lines: $y = -0.2254x$
371 $+ 492.6$ [FE1]; $y = -0.2254x + 536.4$ [FE2]).

372 Maris Widgeon's much lower saccharification potential than the semi-dwarf cultivars
373 skews these relationships and without the inclusion of Maris Widgeon, the
374 relationship between saccharification potential and material strength is not
375 significant. The relationship between saccharification potential and leverage force is
376 still significant without Maris Widgeon but the regression line is much shallower
377 showing only a minor change in saccharification potential with increasing leverage
378 force. The relationship between height and saccharification potential is also
379 significant when excluding Maris Widgeon.

380 ***3.4.3 Lodging resistance and straw yield***

381 In FE1 and FE2 (without PGRs) there was a strong positive relationship between
382 straw yield and plant height ($P < 0.001$; adj. $R^2 = 0.62$. Regression lines: $y =$
383 $0.005495x + 0.904$ [FE1]; $y = 0.010755x - 1.356$ [FE2]) with a difference between
384 field experiments ($P < 0.001$) but with a greater increase in straw yield per unit height
385 in FE2 ($P = 0.003$). This reflected the difference in growing conditions and the
386 greater straw yields seen in 2011. Maris Widgeon had high leverage on the results
387 reflecting it being much taller than the other cultivars.

388 As plant height (given as height at centre of gravity in the model) strongly influences
389 lodging resistance it would be expected that there would be a negative correlation
390 between straw yield and lodging resistance. However, regression analysis
391 demonstrated a positive relationship ($P < 0.001$; adj. $R^2 = 0.84$. Regression lines: $y =$
392 $0.081x + 18.263$ [FE1]; $y = 0.081x + 9.423$ [FE2]), albeit, only a very small increase
393 in SFWS is seen when straw yield increases. There was a difference between the

394 field experiments, representing the large difference in mean SFWS between the two
395 field experiments.

396 4. Discussion

397 The field experiments demonstrated variation in the key traits of interest, allowing
398 cultivar selection for individual traits, but when considering all traits no cultivar
399 stood out as an ideal candidate for use as a DPC. The results give some insight into
400 the relationship between key characteristics, which will be important when selecting
401 or breeding a DPC.

402 Maris Widgeon had a similar AGDM yield to the semi-dwarf cultivars but the
403 biomass was partitioned differently, with Maris Widgeon consistently having the
404 lowest grain yield and highest straw yield. Among the semi-dwarf cultivars the yields
405 tended to be inconsistent between years though this is common (Austin et al., 1980;
406 Shearman et al., 2005) due to variation in weather. For example, regional statistics
407 showed average yields of 7.9, 8.0 and 6.4 t ha⁻¹ for 2010, 2011 and 2012,
408 respectively (Defra, 2015). The high grain yields in FE2 suggest that rainfall did not
409 limit grain yield though may have retarded stem growth giving lower straw yields
410 and high HI. Growing conditions were initially favourable to high yields in FE3 (as
411 seen by the AGDM) but high rainfall in summer 2012 led to fungal disease that
412 lowered grain yield, which is reflected in the lower HI.

413 Excluding Maris Widgeon, there was a positive relationship between grain and straw
414 yields, which was also seen by Larsen et al. (2012). This may represent variation in
415 productivity among the cultivars with some cultivars better suited to the specific field
416 conditions present; this is supported by the inconsistency in the relative performance
417 of cultivars between years. HI tends to be conservative (Hay, 1995), so as conditions
418 favour higher AGDM, straw yield would increase alongside grain yield. Each

419 cultivar had similar HIs in FE1 and FE2, supporting this conservative HI though
420 FHB in FE3 led to inconsistent and lower HIs.

421 The lack of significant difference in AGDM between the non-semi-dwarf cultivar
422 and the semi-dwarf cultivars supports that AGDM has not increased with breeding.
423 This is in contrast to some studies (Shearman et al., 2005) but in agreement with
424 others (Slafer & Andrade, 1989; Brancourt-Hulmel et al., 2003). An explanation for
425 the lack of significance could be that the current study used a fairly narrow range of
426 release dates, with only one non-semi-dwarf cultivar, whereas other studies have had
427 much wider ranges.

428 The positive correlation between grain and straw yields suggests that managing for
429 higher grain yields will give higher straw yields so limitations on straw yield will
430 depend on the limitations for higher grain yields. Increasing straw yield without
431 compromising grain yield is a central idea for developing DPCs. However, as
432 discussed in Townsend et al. (2015), HI is reaching its upper limits and, therefore,
433 further increases in grain yield will necessitate increases in AGDM. In fact, the HIs
434 for some cultivars in FE2 are approaching the hypothesised upper limit for HI of 0.64
435 (Foulkes et al., 2011) and similar HIs at this location have been recorded in previous
436 work (Whaley et al., 2000).

437 In agreement with the majority of the literature, saccharification potential of pre-
438 treated straw residue after enzyme hydrolysis varied among cultivars. Interestingly,
439 Maris Widgeon, the only non-semi-dwarf cultivar, had the lowest straw
440 saccharification potential in both years; as its overall glucose yield for untreated and
441 pre-treated straw did not significantly differ from the other cultivars this suggests

442 that the material was more difficult to break down to release the glucose. This is in
443 agreement with other studies that found that saccharification potential is not
444 correlated with the cellulose present in the material (Murozuka et al., 2015). Capper
445 (1988) suggested that taller cultivars would have lower saccharification potential due
446 to having more stem relative to leaf than shorter cultivars; however, this was not
447 measured in the current study. In contrast to the current study Bellucci et al. (2015)
448 found an increase in saccharification potential with increasing plant height.
449 Lindedam et al. (2012) did not find a relationship between leaf-to-stem ratio and
450 saccharification potential, suggesting that cultivar-specific relationships of leaf and
451 stem sugar yield is more important in predicting the overall saccharification
452 potential. One difficulty in considering leaf-to-stem ratio is that in the senesced state,
453 the leaf blades are friable and are likely to be lost during harvesting. There are many
454 factors that can influence saccharification potential (Townsend et al., 2015) but the
455 current study did not attempt to determine reasons for differences observed in this
456 trait. Interestingly, even though Maris Widgeon had the lowest saccharification
457 potential, because it had much higher straw yield it is likely to have a greater
458 bioethanol yield per unit area of crop.

459 There was little difference in lodging susceptibility among cultivars in each FE even
460 with Maris Widgeon, which, as the only non-semi-dwarf cultivar, would be expected
461 to have much greater risk of lodging. Maris Widgeon had the highest straw yield and
462 was the tallest cultivar yet it was less susceptible to lodging than some of the semi-
463 dwarf cultivars at that growth stage. This resulted from it having a small ear area,
464 which reduced its leverage force, and a slightly higher stem material strength. The

465 higher lodging resistance in FE1 is due to a slightly smaller ear area resulting in
466 lower stem leverage force.

467 To reduce future lodging risk Berry et al. (2007) proposed a lodging resistance wheat
468 ideotype; they suggested more biomass would be required in the lower stem to
469 increase stem material strength. Interestingly, this would require higher straw yield.
470 One important consideration is how this would impact on saccharification potential
471 and conversely whether changes to increase saccharification potential might lower
472 lodging resistance. Selecting cultivars for higher saccharification potential has been
473 suggested to lead to lower lodging resistance due to a negative relationship between
474 saccharification potential and stem material strength; the results of our study also
475 suggest that as saccharification potential increases, material strength decreases but
476 overall lodging resistance (i.e. SFWS) increases. This is partly explained by the
477 decrease in saccharification potential with increasing plant height. The current study
478 did suggest that material strength would be lower with higher saccharification
479 potential. This did not follow through to overall lodging susceptibility due to the
480 negative correlation between saccharification potential and plant height/stem
481 leverage force. It has been suggested that improving saccharification potential could
482 lead to greater risk of lodging but the opposite was found in this study. An important
483 caveat from this study is that some relationships among traits were only seen because
484 of the inclusion of the non-semi-dwarf cultivar Maris Widgeon.

485 Alongside cultivar choice, other management practices might influence the key traits
486 of a DPC. Application of the PGR chlormequat did not significantly reduce straw
487 yields, as previously reported in a number of crops (Bragg et al., 1984; Cox & Otis,
488 1989; Naylor, 1989; Rajala & Peltonen-Sainio, 2001). There is a caveat to this

489 though, as at higher cutter heights there was a significant reduction in straw yield
490 when chlormequat was applied (the lack of significance in published studies could be
491 due to the inclusion of straw that would normally be left on the field as stubble);
492 however, the actual difference in yield was minor and unlikely to warrant changing
493 farming practices. Considering that chlormequat did not have a significant effect on
494 overall straw yield but increased the SFWS while not affecting saccharification
495 potential suggests that farmers should continue to use chlormequat even when
496 supplying straw for biofuel production. There is anecdotal evidence that some
497 farmers are not applying PGRs in order to have higher straw yields for livestock but
498 it may be providing little benefit while increasing lodging risk.

499 Nitrogen application rate only had very limited effect on grain and straw yields; it is
500 likely that dry weather after the final nitrogen fertiliser application, meant that the
501 fertiliser was not washed into the soil and therefore N availability was similar for all
502 three treatments.

503 Decreasing the cutter bar height increased straw yields but there is a trade-off
504 between having these higher straw yields and the higher fuel costs; energy in straw
505 and the energy required to collect that additional straw (Špokas & Steponavičius,
506 2010). However, there are potential benefits of removing as much as possible if a
507 lower-intensity tillage practice is used afterwards as crop residue can harbour pests
508 and disease (Carter, 1994). Cutter height determined whether significant differences
509 in straw yield were seen among cultivars but that actual differences in yield were
510 very small.

511 As this study only captured cultivar characteristics for a limited number of cultivars
512 grown under a limited range of conditions, and there is only limited data from other
513 studies, it is possible that among currently grown cultivars there are those with
514 characteristics suited to the role of a DPC. However, based on our study, should
515 farmers wish to grow straw for bioenergy, they should base their cultivar choice on
516 grain yield potential for their location. Currently, farmers in the UK are provided
517 with metrics on cultivar characteristics (for example, the AHDB's Recommended
518 Lists) but these do not include straw metrics. This lack of availability reflects the
519 limited demand for these metrics. From this study, the limited variation in straw
520 yields among cultivars, but variation between years, suggests that assigning values to
521 individual cultivars would be difficult.

522 Breeding techniques offer the opportunity for improving key characteristics. As the
523 relationships found in this paper suggest, breeding crops for higher grain yields
524 might lead to higher straw yields. Breeding for higher saccharification potential has
525 been suggested as a possibility due to the variation seen among cultivars (Jensen et
526 al., 2011) though Bellucci et al. (2015) found only a limited genetic effect. Greater
527 saccharification potential did not lead to a reduction in the other key traits for the
528 cultivar assessed so targeted breeding for this trait might have potential. Genetic
529 modification techniques could provide the best means of increasing saccharification
530 potential although there would be significant barriers to growing these crops in the
531 EU. One consideration is that although differences in saccharification potential were
532 seen in this study, as discussed in Townsend et al. (2015), it is unclear how these
533 differences would relate to industrial-scale processing. As with other studies, the pre-
534 treatment conditions were selected to achieve 50% subsequent saccharification of

535 glucose from a standard wheat cultivar. This allowed the identification of variations
536 in saccharification potential between cultivars yet possibly does not reflect the
537 industrial process.

538 **5. Conclusions**

539 The field experiments did not identify any outstanding DCPs as, among the high
540 grain-yielding cultivars, straw yields were similar. While there were no outstanding
541 DPC candidates, our data suggest that growers supplying straw should select high
542 grain-yielding cultivars and do not need to change management practices for existing
543 cultivars because higher grain yield gives higher straw. PGRs should be used as they
544 have only a minimal impact on straw yields but reduce lodging risk. Although
545 saccharification potential did vary among cultivars, currently growers and breeders
546 should not consider saccharification potential; for growers there is no financial
547 incentive for growing higher saccharification potential material while for breeders it
548 will be necessary to see the pretreatment methods utilised at the commercial-scale in
549 order to determine the merit of developing higher saccharification potential cultivars.

550

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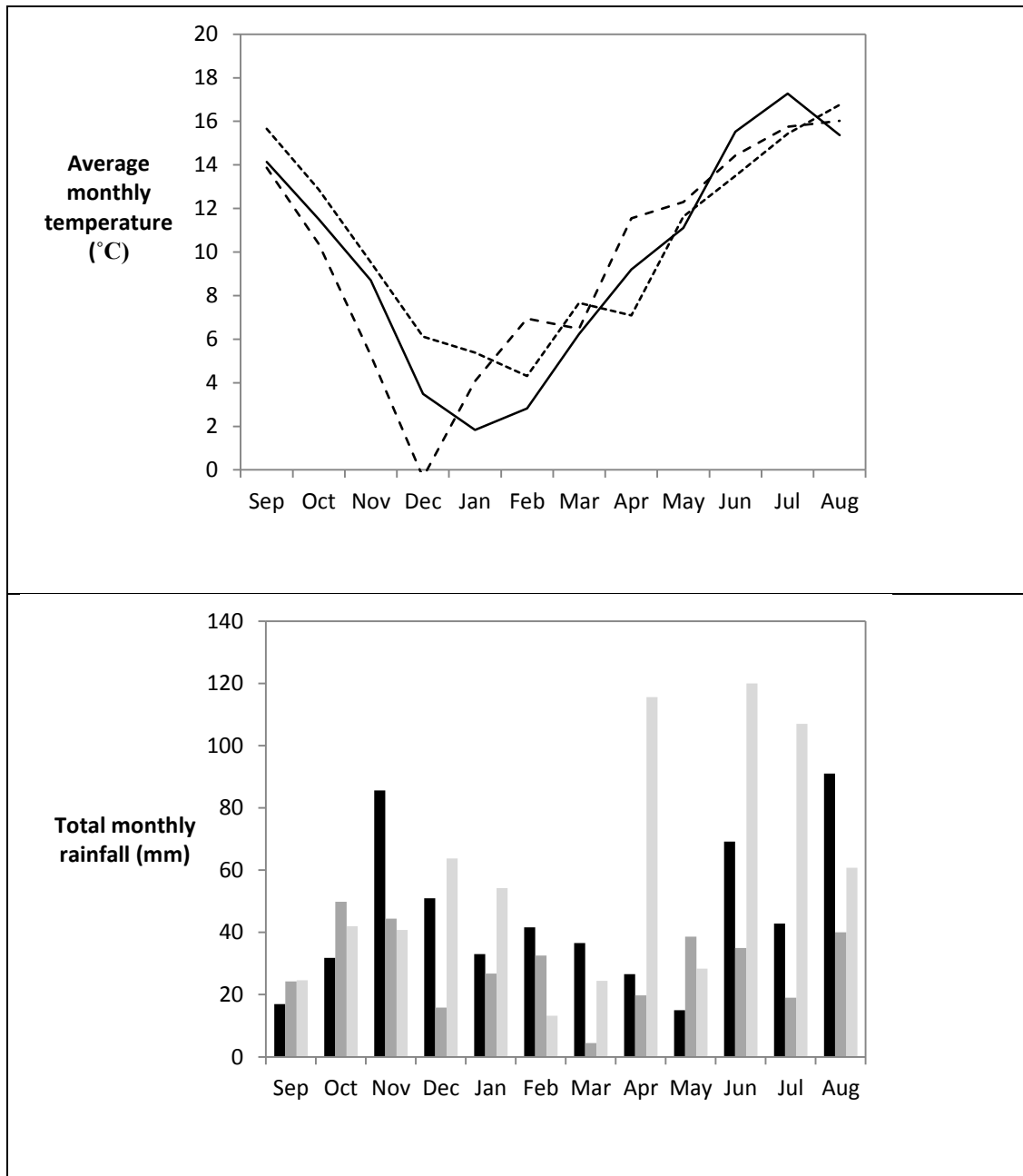
660

661 **Figure captions**

662 **Figure 1a,b:** **a)** average monthly temperature for FE1 (solid line), FE2 (large dashes)
663 and FE3 (small dashes), and **b)** total monthly rainfall for FE1 (black bar), FE2 (dark
664 grey bar) and FE3 (light grey bar). Measured at Sutton Bonington meteorological
665 centre.

666

667 **Figure 1a,b.**



668

669 **Tables**670 **Table 1**

671 Field experiments key information

| | Field experiment | | |
|---------------|---|---|--|
| | FE1 | FE2 | FE3 |
| Sowing date | 20/10/2009 | 13/10/2010 | 06/10/2011 |
| Previous crop | Winter oats | Winter oats | Winter oats |
| SNS N Index | 101.4 kg ha ⁻¹ , SNS Index 2 (12/11/09) | 32.9 kg ha ⁻¹ , SNS Index 0 (09/09/10) | 18.9 kg ha ⁻¹ , SNS Index 0 (23/02/12) |
| Soil Indices | P:5, k:4, Mg:6, pH:6.8 | P:4, K:3, Mg:4, pH:7.2 | P:4, K:4, Mg:4, pH:7.6 |
| Cultivations | Plough (16/09/09); Power harrow (16/10/09); Roll after drilling (22/10/09) | Plough (16/09/10); Power harrow (11/10/10); Roll after drilling (14/10/10) | Plough (13/09/10); Power harrow (22/09/10); Roll after drilling (06/10/10) |
| Seed rate | 250 seeds m ⁻² | 250 seeds m ⁻² | 250 seeds m ⁻² |
| Design | Randomised block design | Split plot | Split-split plot |
| Fertiliser | 1.0 L ha ⁻¹ Manganese Jett (09/11/09); 148 kg ha ⁻¹ 27N 9SO ₃ (40 kg ha ⁻¹ N, 13.3 kg ha ⁻¹ SO ₃ ; 03/03/10); 1 L ha ⁻¹ Human Extra, 232 kg ha ⁻¹ 34.5% Nitram (80 kg ha ⁻¹ N; 08/04/10); 1 L ha ⁻¹ Human Extra (28/04/10); 159 kg ha ⁻¹ 34.5% Nitram (55 kg ha ⁻¹ N; 14/05/10); 1.23 L ha ⁻¹ Magnor (27/05/10). | 87 kg ha ⁻¹ 34.5% Nitram (30 kg ha ⁻¹ N; 08/03/11); 1 L ha ⁻¹ Human Extra (08/03/11); 1 L ha ⁻¹ Human Extra (25/03/11); 232 kg ha ⁻¹ 34.5% Nitram (80 kg ha ⁻¹ N; 06/04/11); 1 L ha ⁻¹ Human Extra (20/04/11); 174 kg ha ⁻¹ 34.5% Nitram (60 kg ha ⁻¹ N; 06/05/11); 1 L ha ⁻¹ Magnor (24/05/11) | 2.0 L ha ⁻¹ Headland Jet (24/02/12); 116 kg/ha 34.5% Nitram (40 kg ha ⁻¹ N; 08/03/12); 2 L ha ⁻¹ Headland Jett (20/03/12); 232 kg/ha 34.5% Nitram (80 kg ha ⁻¹ N; 11/04/12); Manganese 15% @ 1.5 L ha ⁻¹ (30/04/12); Various rates of N (see trial plan for rates; 10/05/12); Magnor @ 1 L ha ⁻¹ (23/05/12); Magnor @ 1 L ha ⁻¹ (25/05/12). |
| Herbicide | 3.0 L ha ⁻¹ Picon C (09/11/09); 1.2 L ha ⁻¹ Hatra, 1.0 L ha ⁻¹ Biopower (27/04/10); | 1 L ha ⁻¹ Hatra, 1.7 L ha ⁻¹ Picon, 1 L ha ⁻¹ Biopower (08/03/11); 1 L ha ⁻¹ Spitfire | 0.6 L ha ⁻¹ Liberator (09/11/2011); 25g ha ⁻¹ Lorate (20/03/12); 1 L ha ⁻¹ Foxtrot & 1 L |

| | | | |
|-------------|--|--|---|
| | 1.23 L ha ⁻¹ Starane XL (27/05/10). | (24/05/11) | ha ⁻¹ Toil (24/04/12); 1 L ha ⁻¹ Spitfire (23/05/12) |
| Fungicide | 0.75 L ha ⁻¹ Alto Elite (08/04/10); 0.65 L ha ⁻¹ Proline, 0.75 L ha ⁻¹ Amistar Opti (28/04/10); 1.23 L ha ⁻¹ Brutus, 1.23 L ha ⁻¹ Amistar Opti, 0.5 L ha ⁻¹ Corbel (27/05/10); 0.75 L ha ⁻¹ Folicur, 0.5 L ha ⁻¹ Corbel, 0.15 L ha ⁻¹ Justice (09/07/10). | 0.75 L ha ⁻¹ Alto Elite, 0.15 L ha ⁻¹ Vegas (25/03/11); 0.5 L ha ⁻¹ Proline, 0.5 L ha ⁻¹ Alto Elite (20/04/11); 0.5 L ha ⁻¹ Comet, 0.1 L ha ⁻¹ Justice, 0.5 L ha ⁻¹ Proline (24/05/11); 0.75 L ha ⁻¹ Caramba (15/06/11). | 0.75 L ha ⁻¹ Opus, 1.0 L ha ⁻¹ Bravo, 0.4 L ha ⁻¹ Instinct (20/03/12); 0.75 L ha ⁻¹ Cortez, 1.3 L ha ⁻¹ Phoenix (30/04/12); 0.75 L ha ⁻¹ Opus, 1.3 L ha ⁻¹ Phoenix (23/05/12); 0.85 L ha ⁻¹ Orius, 0.15 L ha ⁻¹ Vegas (25/06/12) |
| Insecticide | 0.25 L ha ⁻¹ Permasect (09/11/09) | 0.25 L ha ⁻¹ Permasect (08/03/11); 0.25 L ha ⁻¹ Aphox (15/06/11) | 0.25 L ha ⁻¹ Permasect (09/11/11); 0.28 kg ha ⁻¹ Aphox (25/06/12) |
| PGR | None | 1 L ha ⁻¹ Chlormequat (+PGR plots only; 25/03/11); 0.8 L ha ⁻¹ Chlormequat (+PGR plots only; 20/04/11) | 1 L ha ⁻¹ Chlormequat (+PGR plots only; 22/03/12); 0.8 L ha ⁻¹ Chlormequat (+PGR plots only; 30/04/12). |

673 **Table 2**

674 Cultivars assessed in field experiments. Source: AHDB Recommended Lists for
 675 cereals and oilseeds 2009, 2010 and 2011. N.B. Maris Widgeon predates AHDB
 676 Recommended Lists so data is not available on these key parameters; the date refers
 677 to the year of introduction (Austin et al., 1980). Field experiments: 1, 2 and 3. Nabim
 678 groups refer to the grain end-use (i.e. whether it is suited to milling or animal feed).
 679 A rating of 1 refers to milling quality while 4 is for feed wheat.

| Cultivar | Field experimen t | NABI M group | Resistanc e to lodging without PGR | Resistanc e to lodging with PGR | Height withou t PGR (cm) | Heigh t with PGR (cm) | Year first liste d |
|------------------|-------------------------|--------------------|--|--|-----------------------------------|--------------------------------|-----------------------------|
| Hereward | 1, 2 | 1 | 8 | 9 | 88 | - | 1991 |
| Mascot | 1, 2 | 1 | 6 | 8 | 93 | 84 | 2006 |
| Xi19 | 1, 2, 3 | 1 | 4 | 6 | 97 | 88 | 2002 |
| Battalion | 1, 2 | 2 | 7 | 8 | 88 | 82 | 2007 |
| Cordiale | 1, 2, 3 | 2 | 8 | 9 | 82 | 76 | 2004 |
| Sterling | 1, 2 | 2 | 6.7 | 8.3 | 80 | - | 2010 |
| Invicta | 1, 2 | 3 | 7.2 | 7.5 | 93 | 86 | 2010 |
| Riband | 1, 2 | 3 | 8 | 8 | 89 | - | 1989 |
| Zebedee | 1, 2 | 3 | 6 | 6 | 87 | 84 | 2007 |
| Ambrosi a | 1, 2 | 4 | 7 | 8 | 88 | 80 | 2005 |
| Glasgow | 2 | 4 | 6 | 8 | 85 | 74 | 2005 |
| Grafton | 1, 2, 3 | 4 | 9 | 9 | 79 | 72 | 2009 |
| Istabraq | 1, 2 | 4 | 6 | 7 | 96 | 88 | 2004 |
| Quartz | 1, 2 | 4 | 9 | 9 | 75 | - | 2009 |
| Maris Widgeon | 1, 2 | - | - | - | - | - | 1964 |

680

681 **Table 3**

682 Yield components of cultivars grown in FE1. ANOVA statistical output with degrees
683 of freedom (d.f.) and standard error of the differences between means (SED).

| Cultivars | AGDM (t ha ⁻¹) | Grain Yield (t ha ⁻¹) | Straw Yield (t ha ⁻¹) | Harvest Index |
|---------------|-------------------------------|--------------------------------------|--------------------------------------|---------------|
| Ambrosia | 14.50 | 8.28 | 4.76 | 0.57 |
| Battalion | 14.57 | 8.21 | 4.81 | 0.56 |
| Cordiale | 17.07 | 9.98 | 5.20 | 0.58 |
| Grafton | 12.86 | 7.43 | 3.98 | 0.58 |
| Hereward | 14.22 | 7.80 | 4.76 | 0.55 |
| Invicta | 14.24 | 7.68 | 5.05 | 0.53 |
| Istabraq | 13.84 | 7.82 | 4.58 | 0.56 |
| Maris Widgeon | 13.56 | 5.61 | 6.68 | 0.42 |
| Mascot | 14.02 | 8.13 | 4.46 | 0.58 |
| Quartz | 13.19 | 7.67 | 4.00 | 0.58 |
| Riband | 15.87 | 9.05 | 5.17 | 0.57 |
| Sterling | 12.84 | 7.22 | 4.15 | 0.56 |
| Xi 19 | 16.65 | 9.30 | 5.47 | 0.56 |
| Zebedee | 13.05 | 7.51 | 4.13 | 0.57 |
| Mean | 14.32 | 7.98 | 4.80 | 0.56 |
| P | NS | 0.048 | 0.005 | <0.001 |
| SED | 1.720 | 1.039 | 0.594 | 0.014 |
| df | 39 | 39 | 39 | 39 |

684

685 **Table 4**

686 Yield components of cultivars grown in FE2. ANOVA statistical output with degrees
687 of freedom (d.f.) and standard error of the differences between means (SED).

| Treatment | | AGDM (t ha ⁻¹) | Grain Yield (t ha ⁻¹) | Straw Yield (t ha ⁻¹) | Harvest Index |
|-----------|---------------|-------------------------------|--------------------------------------|--------------------------------------|---------------|
| Cultivar | Ambrosia | 20.10 | 11.83 | 6.59 | 0.59 |
| | Battalion | 18.18 | 10.51 | 6.05 | 0.58 |
| | Cordiale | 17.23 | 10.34 | 5.30 | 0.60 |
| | Glasgow | 20.45 | 12.34 | 6.15 | 0.61 |
| | Grafton | 18.05 | 10.93 | 5.52 | 0.61 |
| | Hereward | 18.88 | 10.36 | 6.55 | 0.55 |
| | Invicta | 19.24 | 11.04 | 6.54 | 0.57 |
| | Istabraq | 20.13 | 11.50 | 6.81 | 0.57 |
| | Maris Widgeon | 18.19 | 7.89 | 8.75 | 0.44 |
| | Mascot | 18.97 | 10.87 | 6.43 | 0.57 |
| | Quartz | 17.15 | 10.41 | 5.41 | 0.59 |
| | Riband | 18.58 | 11.25 | 5.82 | 0.61 |
| | Sterling | 16.41 | 9.66 | 5.26 | 0.59 |
| | Xi 19 | 18.96 | 11.33 | 5.88 | 0.60 |
| | Zebedee | 18.74 | 11.13 | 5.99 | 0.59 |
| PGR | PGR+ | 18.00 | 10.53 | 5.85 | 0.58 |
| | PGR- | 19.23 | 10.95 | 6.55 | 0.57 |
| Mean | | 18.62 | 10.74 | 6.2 | 0.58 |
| Cultivar | P | NS | <0.001 | <0.001 | <0.001 |
| | SED | 1.357 | 0.780 | 0.508 | 0.007 |
| | df | 56 | 56 | 56 | 56 |
| PGR | P | NS | NS | NS | NS |
| | SED | 0.645 | 0.286 | 0.318 | 0.004 |
| | df | 2 | 2 | 2 | 2 |

688

689 **Table 5**

690 Yield components of cultivars grown in FE3. ANOVA statistical output with degrees
691 of freedom (d.f.) and standard error of the differences between means (SED).

| Treatment | | AGDM (t ha ⁻¹) | Grain Yield (t ha ⁻¹) | Straw Yield (t ha ⁻¹) | Harvest Index |
|-----------|----------|-------------------------------|--------------------------------------|--------------------------------------|---------------|
| Cultivar | Cordiale | 20.60 | 8.15 | 9.14 | 0.47 |
| | Grafton | 20.54 | 8.10 | 9.16 | 0.46 |
| | Xi19 | 19.08 | 6.76 | 9.11 | 0.42 |
| PGR | PGR+ | 20.36 | 7.89 | 9.07 | 0.45 |
| | PGR- | 19.79 | 7.45 | 9.20 | 0.44 |
| N | N1 | 19.97 | 7.73 | 8.93 | 0.46 |
| | N2 | 20.13 | 7.51 | 9.47 | 0.44 |
| | N3 | 20.11 | 7.76 | 9.01 | 0.45 |
| Mean | | 20.07 | 7.67 | 9.14 | 0.45 |
| Cultivar | P | 0.017 | <0.001 | NS | <0.001 |
| | SED | 0.550 | 0.256 | 0.272 | 0.009 |
| | d.f | 24 | 24 | 24 | 24 |
| PGR | P | NS | 0.040 | NS | NS |
| | SED | 0.363 | 0.169 | 0.231 | 0.006 |
| | d.f | 6 | 6 | 6 | 6 |
| N | P | NS | NS | NS | NS |
| | SED | 0.578 | 0.559 | 0.218 | 0.022 |
| | d.f | 4 | 4 | 4 | 4 |

692

693

694 **Table 6**

695 Straw section yields (t ha⁻¹) from FE3. ANOVA statistical output with degrees of
696 freedom (d.f.) and standard error of the differences between means (SED).

| Treatment | | Cutter height | | |
|-----------|----------|---------------|-------|-------|
| | | 10 cm | 15 cm | 20 cm |
| Cultivar | Cordiale | 4.71 | 4.12 | 3.57 |
| | Grafton | 4.50 | 3.90 | 3.33 |
| | Xi19 | 4.90 | 4.34 | 3.82 |
| PGR | PGR+ | 4.62 | 4.01 | 3.45 |
| | PGR- | 4.79 | 4.23 | 3.70 |
| N | N1 | 4.51 | 3.93 | 3.40 |
| | N2 | 4.91 | 4.31 | 3.75 |
| | N3 | 4.69 | 4.12 | 3.58 |
| Mean | | 4.70 | 4.12 | 3.57 |
| Cultivar | P | 0.036 | 0.007 | 0.001 |
| | SED | 0.146 | 0.127 | 0.178 |
| | d.f | 24 | 24 | 24 |
| PGR | P | NS | 0.036 | 0.009 |
| | SED | 0.107 | 0.082 | 0.066 |
| | d.f | 6 | 6 | 6 |
| N | P | NS | NS | NS |
| | SED | 0.160 | 0.159 | 0.159 |
| | d.f | 4 | 4 | 4 |

697

698

699 **Table 7**

700 Saccharification potential traits of cultivars in FE1. ANOVA statistical output with degrees of freedom (d.f.) and standard error of the
701 differences between means (SED).

| Cultivars | Untreated glucose | Untreated xylose | Pretreated glucose | Saccharification potential | % saccharification potential |
|------------------|------------------------------|-----------------------------|--------------------------------------|---------------------------------------|---|
| | (mg g ⁻¹ straw) | (mg g ⁻¹ straw) | (mg g ⁻¹ preteated straw) | (mg g ⁻¹ pretreated straw) | - |
| Cordiale | 265 | 167 | 639 | 344 | 54.0 |
| Hereward | 244 | 161 | 643 | 324 | 50.6 |
| Maris Widgeon | 282 | 123 | 634 | 244 | 38.7 |
| Quartz | 241 | 165 | 623 | 374 | 60.3 |
| Riband | 251 | 157 | 633 | 336 | 53.1 |
| Zebedee | 234 | 156 | 631 | 339 | 54.0 |
| Mean | 253 | 155 | 634 | 327 | 51.8 |
| P | NS | NS | NS | <0.001 | <0.001 |
| SED | 15.0 | 24.5 | 15.0 | 9.7 | 1.78 |
| df | 15 | 15 | 15 | 15 | 15 |

702

704 **Table 8**

705 Saccharification potential traits of cultivars in FE2. ANOVA statistical output with degrees of freedom (d.f.) and standard error of the
706 differences between means (SED).

| Treatment | | Untreated glucose | Untreated xylose | Pretreated glucose | Saccharificat ion potential | % glucose release |
|-----------|---------------|-----------------------|-----------------------|-----------------------|--------------------------------|-------------------|
| | | (mg g ⁻¹) | (mg g ⁻¹) | (mg g ⁻¹) | (mg g ⁻¹) | - |
| Cultivar | Cordiale | 302 | 155 | 581 | 391 | 67.5 |
| | Hereward | 277 | 148 | 571 | 376 | 66.0 |
| | Istabraq | 289 | 154 | 593 | 370 | 62.7 |
| | Maris Widgeon | 288 | 143 | 584 | 315 | 54.1 |
| | Quartz | 265 | 153 | 605 | 405 | 67.1 |
| | Riband | 288 | 150 | 598 | 381 | 64.0 |
| | Zebedee | 266 | 150 | 579 | 381 | 66.0 |
| PGR | PGR+ | 290 | 149 | 591 | 381 | 64.7 |
| | PGR- | 275 | 149 | 584 | 367 | 63.2 |
| Mean | | 282 | 149 | 587 | 374 | 63.9 |
| Cultivar | P | NS | NS | NS | <0.001 | <0.001 |
| | SED | 18.4 | 4.2 | 13.1 | 10.7 | 2.52 |
| | df | 24 | 24 | 24 | 24 | 24 |
| PGR | P | NS | NS | NS | NS | NS |

| | | | | | |
|-----|-------|------|------|------|-------|
| SED | 34.64 | 7.36 | 5.98 | 6.23 | 0.991 |
| df | 2 | 2 | 2 | 2 | 2 |

707 **Table 9**

708 Lodging components from FE1. I1 and I2 refer to internodes 1 and 2, respectively. ANOVA statistical output with degrees of freedom (d.f.) and
 709 standard error of the differences between means (SED).

| Cultivar | SFWS (m s ⁻¹) | Leverage force (Nmm) | | Stem material strength (MPa) | | HCG (mm) |
|---------------|------------------------------|----------------------|--------|------------------------------|------|-------------|
| | | I1 | I2 | I1 | I2 | |
| Ambrosia | 19.27 | 127.6 | 108.7 | 43.1 | 27.8 | 427.9 |
| Battalion | 17.80 | 103.0 | 86.5 | 33.9 | 24.8 | 414.4 |
| Cordiale | 19.71 | 93.1 | 79.0 | 47.4 | 33.2 | 393.7 |
| Grafton | 21.02 | 103.2 | 88.6 | 38.5 | 29.2 | 384.9 |
| Hereward | 19.05 | 116.1 | 100.7 | 53.1 | 30.3 | 436.1 |
| Invicta | 17.72 | 153.9 | 132.3 | 41.2 | 32.2 | 472.8 |
| Istabraq | 18.22 | 161.6 | 138.6 | 44.1 | 32.4 | 473.2 |
| Maris Widgeon | 16.08 | 184.1 | 160.9 | 49.0 | 35.3 | 582.5 |
| Mascot | 19.02 | 133.8 | 115.7 | 39.7 | 23.2 | 458.5 |
| Quartz | 20.27 | 99.4 | 85.5 | 34.9 | 27.1 | 380.5 |
| Riband | 19.47 | 125.3 | 107.8 | 39.0 | 27.8 | 440.4 |
| Sterling | 18.97 | 112.5 | 96.1 | 38.2 | 30.3 | 399.0 |
| Xi 19 | 19.72 | 137.8 | 117.9 | 44.9 | 34.0 | 465.6 |
| Zebedee | 14.78 | 149.8 | 127.9 | 30.1 | 21.5 | 439.7 |
| Mean | 18.65 | 128.7 | 110.4 | 41.2 | 29.2 | 440.7 |
| P | <0.001 | <0.001 | <0.001 | NS | NS | <0.001 |
| SED | 1.011 | 8.83 | 7.86 | 7.83 | 4.27 | 11.46 |

| | | | | | | |
|----|----|----|----|----|----|----|
| df | 39 | 39 | 39 | 39 | 39 | 39 |
|----|----|----|----|----|----|----|

710 **Table 10**

711 Lodging components from FE2. I1 and I2 refer to internodes 1 and 2, respectively. ANOVA statistical output with degrees of freedom (d.f.) and
 712 standard error of the differences between means (SED).

| Cultivar | PGR treatment | SFWS (m s ⁻¹) | Leverage force (Nmm) | | Stem material strength (MPa) | | HCG (mm) |
|---------------|------------------|------------------------------|----------------------|-------|---------------------------------|-------|-------------|
| | | | I1 | I2 | I1 | I2 | |
| Ambrosia | PGR- | 9.83 | 147.7 | 147.7 | 29.12 | 11.45 | 452.7 |
| | PGR+ | 11.20 | 127.1 | 127.1 | 33.49 | 12.57 | 422.8 |
| Battalion | PGR- | 10.76 | 137.0 | 137.0 | 32.37 | 16.09 | 461.5 |
| | PGR+ | 11.25 | 97.8 | 97.8 | 28.86 | 12.06 | 406.8 |
| Cordiale | PGR- | 10.08 | 159.6 | 159.6 | 51.69 | 15.60 | 458.5 |
| | PGR+ | 10.39 | 110.8 | 110.8 | 30.97 | 14.89 | 415.5 |
| Glasgow | PGR- | 10.52 | 158.9 | 158.9 | 27.36 | 14.81 | 473.8 |
| | PGR+ | 10.51 | 124.0 | 124.0 | 26.90 | 12.22 | 432.5 |
| Grafton | PGR- | 12.64 | 128.7 | 128.7 | 38.60 | 15.10 | 416.2 |
| | PGR+ | 13.50 | 100.8 | 100.8 | 28.86 | 16.29 | 389.5 |
| Hereward | PGR- | 10.38 | 127.0 | 127.0 | 42.11 | 13.95 | 456.0 |
| | PGR+ | 11.27 | 107.5 | 107.5 | 31.79 | 12.08 | 417.3 |
| Invicta | PGR- | 10.64 | 180.7 | 180.7 | 30.87 | 15.56 | 496.9 |
| | PGR+ | 11.34 | 171.3 | 171.3 | 28.81 | 13.46 | 479.0 |
| Istabraq | PGR- | 9.19 | 184.2 | 184.2 | 30.22 | 12.39 | 501.8 |
| | PGR+ | 11.64 | 166.1 | 166.1 | 41.86 | 20.08 | 465.3 |
| Maris Widgeon | PGR- | 8.52 | 201.8 | 201.8 | 40.19 | 15.97 | 591.6 |

| | | | | | | | |
|--------------|------|--------|--------|--------|-------|-------|--------|
| Mascot | PGR+ | 10.83 | 166.6 | 166.6 | 41.64 | 23.73 | 550.0 |
| | PGR- | 10.18 | 179.3 | 179.3 | 28.20 | 14.06 | 491.0 |
| Quartz | PGR+ | 11.02 | 117.5 | 117.5 | 21.42 | 12.61 | 421.7 |
| | PGR- | 9.70 | 128.5 | 128.5 | 28.37 | 9.45 | 408.3 |
| Riband | PGR+ | 12.98 | 107.6 | 107.6 | 28.31 | 21.62 | 387.0 |
| | PGR- | 9.73 | 159.8 | 159.8 | 26.70 | 9.38 | 467.8 |
| Sterling | PGR+ | 11.62 | 128.6 | 128.6 | 25.90 | 9.74 | 433.2 |
| | PGR- | 9.24 | 152.5 | 152.5 | 34.71 | 11.79 | 429.3 |
| Xi 19 | PGR+ | 11.74 | 128.7 | 128.7 | 32.16 | 21.83 | 417.3 |
| | PGR- | 9.08 | 194.5 | 194.5 | 35.00 | 16.23 | 511.5 |
| Zebedee | PGR+ | 11.75 | 139.8 | 139.8 | 26.77 | 17.92 | 454.0 |
| | PGR- | 8.79 | 187.7 | 187.7 | 24.92 | 12.86 | 464.0 |
| | PGR+ | 9.43 | 160.3 | 160.3 | 26.63 | 14.64 | 445.4 |
| Mean | | 10.66 | 159.4 | 146.1 | 31.83 | 14.68 | 453.9 |
| Cultivar | P | <0.001 | <0.001 | <0.001 | 0.002 | NS | <0.001 |
| | SED | 0.659 | 6.61 | 6.35 | 4.333 | 3.114 | 6.48 |
| | df | 56 | 56 | 56 | 56 | 56 | 56 |
| PGR | P | 0.026 | 0.001 | <0.001 | NS | NS | <0.001 |
| | SED | 0.230 | 1.13 | 0.90 | 0.967 | 1.664 | 0.59 |
| | df | 2 | 2 | 2 | 2 | 2 | 2 |
| PGRxCultivar | P | NS | 0.002 | 0.005 | NS | NS | 0.002 |
| | SED | 0.930 | 9.11 | 8.73 | 5.999 | 4.568 | 8.87 |
| | df | 56 | 56 | 56 | 56 | 56 | 56 |

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714

715 **Table 11**

716 Lodging components from FE3. I1 and I2 refer to internodes 1 and 2, respectively.
 717 ANOVA statistical output with degrees of freedom (d.f.) and standard error of the
 718 differences between means (SED).

| Cultivar | Nitrogen | PGR | Material strength (MPa) | | Leverage force (Nmm) | | SFWS (m s ⁻¹) | HCG (mm) |
|----------|----------|---------|----------------------------|--------|-------------------------|--------|------------------------------|-------------|
| | | | I1 | I2 | I1 | I2 | | |
| Cordiale | N1 | With | 44.3 | 22.3 | 130.1 | 118.1 | 12.69 | 476.3 |
| | N2 | | 41.6 | 21.6 | 139.1 | 125.6 | 12.51 | 484.0 |
| | N3 | | 42.1 | 22.8 | 148.8 | 138.4 | 11.60 | 496.8 |
| | N1 | Without | 35.3 | 17.9 | 159.9 | 147.6 | 10.36 | 527.0 |
| | N2 | | 48.9 | 25.0 | 173.5 | 156.9 | 11.16 | 540.5 |
| | N3 | | 36.4 | 22.9 | 174.7 | 160.6 | 9.95 | 537.7 |
| Grafton | N1 | With | 26.3 | 15.7 | 137.2 | 123.4 | 11.79 | 466.0 |
| | N2 | | 34.4 | 17.9 | 143.6 | 132.4 | 12.30 | 465.9 |
| | N3 | | 30.4 | 16.8 | 148.6 | 135.3 | 11.60 | 466.2 |
| | N1 | Without | 30.2 | 16.9 | 156.7 | 144.7 | 11.28 | 505.3 |
| | N2 | | 29.1 | 15.8 | 165.2 | 148.7 | 10.07 | 508.7 |
| | N3 | | 29.4 | 14.9 | 171.7 | 155.4 | 10.31 | 506.8 |
| Xi19 | N1 | With | 28.2 | 19.2 | 222.6 | 202.4 | 10.4 | 546.7 |
| | N2 | | 29.5 | 19.7 | 266.8 | 242.6 | 9.18 | 582.2 |
| | N3 | | 32.2 | 20.2 | 269.4 | 245.4 | 9.28 | 565.0 |
| | N1 | Without | 30.2 | 20.4 | 291.8 | 267.9 | 8.78 | 615.3 |
| | N2 | | 27.9 | 19.8 | 311.8 | 286.1 | 9.09 | 620.6 |
| | N3 | | 35.4 | 19.3 | 308.8 | 283.9 | 8.85 | 604.9 |
| Mean | | | 34.0 | 19.4 | 195.6 | 178.6 | 10.62 | 528.7 |
| Cultivar | P | | <0.001 | <0.001 | <0.001 | <0.001 | <0.001 | <0.001 |
| | SED | | 1.56 | 0.99 | 7.49 | 7.17 | 0.255 | 4.08 |
| | df | | 24 | 24 | 24 | 24 | 24 | 24 |
| PGR | P | | NS | NS | 0.001 | <0.001 | 0.001 | <0.001 |
| | SED | | 1.42 | 0.66 | 5.98 | 5.19 | 0.217 | 4.32 |
| | df | | 6 | 6 | 6 | 6 | 6 | 6 |
| Nitrogen | P | | NS | NS | 0.041 | 0.035 | NS | NS |
| | SED | | 2.92 | 0.97 | 5.52 | 4.82 | 0.328 | 8.43 |
| | df | | 4 | 4 | 4 | 4 | 4 | 4 |
| C x PGR | P | | NS | NS | NS | NS | NS | NS |
| | SED | | 2.30 | 1.32 | 10.51 | 9.77 | 0.365 | 6.39 |
| | df | | 24 | 24 | 24 | 24 | 24 | 24 |
| C x N | P | | NS | NS | NS | NS | NS | NS |

| | | | | | | | |
|-------------|-----|-------|------|-------|-------|-------|-------|
| | SED | 3.67 | 1.70 | 11.95 | 11.22 | 0.487 | 10.22 |
| | df | 24 | 24 | 24 | 24 | 24 | 24 |
| N x PGR | P | NS | NS | NS | NS | NS | NS |
| | SED | 3.41 | 1.26 | 9.17 | 7.98 | 0.422 | 9.96 |
| | df | 6 | 6 | 6 | 6 | 6 | 6 |
| N x PGR x C | P | 0.024 | NS | NS | NS | NS | NS |
| | SED | 4.63 | 2.35 | 17.56 | 16.40 | 0.662 | 12.87 |
| | df | 24 | 24 | 24 | 24 | 24 | 24 |

719

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